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Inzhenerno-Fizicheskii Zhurnal (Engineering Physical Journal), Leningrad, 7, 10, pp. 49-55 (1964)

Translated from the Russian

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An analytical description of heat transfer in a model of a granular system is given. New expressions are derived for heat conductivity of granular systems with filling gas under normal and under various pressures.

Most resembling the actual structure of a granular system would be a model with a chaotic distribution of particles having nearly equal volumes and rough surfaces. However, the difficulties connected with calculating the geometrical and physical parameters of such a system make it necessary to idealize the structure of the granular system and to assume for it the presence of a "distant" order in the distribution of the particles. Since the particles have a rough surface, we will separate conditionally the spherical base in each particle and will regard the region occupied by the rough portions as an aureole of uniform thickness.

Assuming that the most probable compact packing of the particles is tetrahedral, a sphere in such a system will rest on three spheres located below it. With a tetrahedral arrangement of the spheres, the porosity is equal to 25.95 percent and is independent of the size of the sphere [1]. In actual systems the larger porosity is due to the irregular shape of the particles, deviation from ideal packing, and other causes.

Let us use a four-layer, most compact packing (the repetition of the first layer begins in the fourth layer), and let us consider the transfer of heat in direction I (Figure 1a).

In any system with a long-range order we can treat separately the smallest volume (an elementary cell) whose innumerable repetition will give us the original system.

In our system the elementary cell is represented by a rectangular parallelepiped (Figure 1b) whose base is a square with a side $d = 2r$ and a height $h = d\sqrt{2}$.

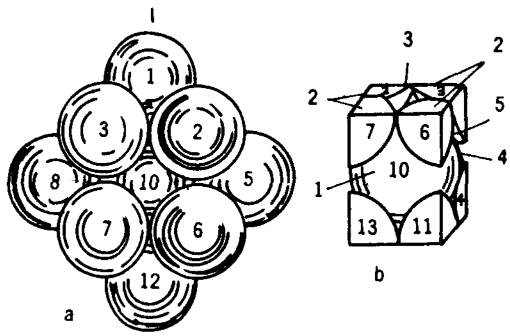

FIGURE 1. MODEL OF A GRANULAR SYSTEM

a) Most compact packing of spheres; b) elementary cell: 1) central solid particle; 2) eight equal parts of solid particle; 3) two halves; 4) four one-quarter parts of octahedrally-shaped large pores; 5) eight halves of octahedrally-shaped small pores.

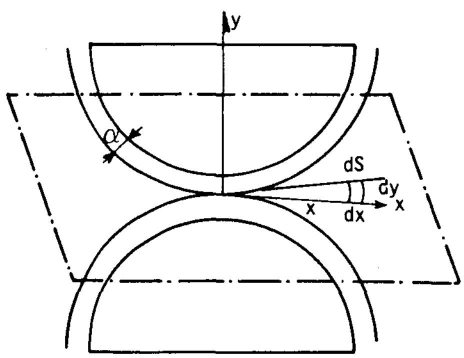

FIGURE 2. FOR CALCULATING THE HEAT CONDUCTIVITY BETWEEN SPHERES

It is not difficult to prove that the effective heat conductivity of a system with a long-range order in distribution of the particles is identical to that of an elementary cell and, therefore, all further discussions will deal only with elementary cells.

We will show how the change in porosity in actual systems ($p > 26$ percent) depends on the size of the aureole α (Figure 2). The volume occupied by solid particles in a granular system is equal to $(100-p)$ and the volume of the gaseous aureoles is $(p-26)$. The ratio of the volume of the gaseous aureole to the volume of the solid particles expressed through geometric parameters is equal to:

$$\frac{p - 26}{100 - p} = 3\frac{\alpha}{r} + 3\frac{\alpha^2}{r^2} + \frac{\alpha^3}{r^3}. \tag{1}$$

Solving equation (1) for (α/r), we obtain

$$A = 1 + \frac{\alpha}{r} = \sqrt[3]{\frac{74}{100 - p}}. \tag{2}$$

The following flows of heat (Figure 1b) pass through an elementary cell by overcoming the resistance R_i. Four identical flows through a part of the solid particles. Four identical flows from the upper particles 2 to the central particle 1 passing through: a) the gaseous aureole (R_1), b) the microclearance between the contacting rough portions (R_2), and c) by direct contact with the particles R_k. A flow to the central particle 1 through one-half of the large pore 3 (R_3). A flow through a part ($\frac{1}{8}$) of the lateral large pores 4 (R_4). Since the resistance of the large pores is zero (an assumption), therefore, all thermal resistances R_i are parallel (the conductivities $\sigma_i = 1/R_i$ are added together).

Assuming that the upper and central planes of the elementary cell are isothermic and taking into consideration that $4\sigma_4 = \sigma_3$, we obtain the following expression for the effective conductivity σ of one-half of the elementary cell:

$$\sigma = \frac{\lambda_{e\phi} S}{0.5h} = \frac{4\lambda_{e\phi} r A}{\sqrt{2}} = 4(\sigma_1 + \sigma_2 + 0.5\sigma_3) + 4\sigma_K. \tag{3}$$

$e\phi$ = effective

It follows from equation (3) that

$$\lambda_{e\phi} = \frac{\sqrt{2}}{rA}(\sigma_1 + \sigma_2 + 0.5\sigma_3) + \lambda_K. \tag{4}$$

$e\phi$ = effective

Consequently, the problem is reduced to a determination of the structure of the heat conductivities. From now on, only dry granular systems will be considered.

We will assume that the resistance of a solid particle is zero (the heat conductivity of the sphere's material is infinitely great) and that the entire temperature drop Δt takes place in the clearance. The thermal flux due to the molecular transfer through the clearance is equal to:

$$dQ_1 = \lambda_r \frac{\Delta t}{2y} dS = \lambda_r \frac{\Delta t}{2y} x dx d\varphi. \tag{5}$$

r = gas

Expressing y through x and integrating the equation (5) for the angle φ within 0 to 2π and for x from 0 to r, we can find the thermal flux through the aureole (the small pores in the cell)

$$Q_1 = \lambda_r \Delta t \pi r \left(A \ln \frac{A}{A-1} - 1\right). \tag{6}$$

r = gas

On the other hand, we have $Q_1 = \Delta t \sigma_1$. A comparison with (6) will give us

$$\sigma_1 = \lambda_r \pi r \left(A \ln \frac{A}{A - 1} - 1 \right). \tag{7}$$

The heat conductivity σ_2 of the gaseous clearance between the contacting rough portions can be expressed by the following relationship:

$$\sigma_2 = \lambda_r S_H / 1.5 h_{\text{Ш}} .$$

H = initial
Ш = sphere
r = gas

Let us first consider the contact of two ideal (free of microroughness) spheres with a radius r and let us find the drawing together of these spheres when acted upon by an outside load and forming thereby an area of a circle S. From the theory of elasticity it follows that the following relationships [2] are valid for contacting smooth spheres subjected to a load:

$$b = \left[\frac{9(1 - \mu^2)^2 P_H^2}{2rE^2} \right]^{1/3}, \quad S = \pi \left[\frac{(1 - \mu^2) 3 P_H 2r}{8E} \right]^{2/3} . \tag{8}$$

H = initial

The expressions (8) will have a different form when the centers of the spheres and the direction of the outside force P_H are not located on the same straight line.

Assume that a certain load whose specific value is designated by Δ is applied normally to the upper plane of an elementary cell. The solid surfaces of the cell's upper plane have an area of $\pi d^2/4$ and, therefore, the value of the load will be $\Delta \pi d^2/4$. This force is distributed among four particles. Taking into account the geometry of the elementary cell, the load per each contact will be

$$P_H = \Delta \pi d^2 / 16 \sqrt{2} .$$

H = initial

Let us assume that the elementary cell is not subjected to lateral deformation, i.e., $\mu = 0$, and that the force P_H produces only a longitudinal deformation; in this case we obtain from equation (8)

$$b = 0.56d \left(\frac{\Delta}{E}\right)^{2/3}, \quad S = 0.14\pi d^2 \left(\frac{\Delta}{E}\right)^{2/3}. \tag{9}$$

Let us introduce the concept of the modulus of elasticity E_0 of the granular system consisting of compactly packed smooth spheres. The relative deformation D of the elementary cell acted upon by the specific load Δ is equal to

$$D = \frac{\Delta}{E_0} = \frac{2b}{h}. \tag{10}$$

From the equations (9) and (10) we obtain the relationship

$$E_0 = 1.3\Delta^{1/3} E^{2/3}.$$

Experiments had shown that

$$E_{0\,exp} = \beta\Delta^{1/3} E^{2/3}, \quad \beta = 0.3 \div 0.6, \tag{11}$$

i.e., $\beta \neq 1.3$, as it follows from the theory. The possible reasons for this discrepancy are as follows: The particles are not arranged as required by an ideal theoretical pattern; the particles have a wavy and rough surface. With this in mind, we will use the expression (11) for approximated calculations.

Taking the relationship (11) into account, we obtain

$$S_H = \frac{0.14\,\pi d^2}{\beta^{2/3}} \left(\frac{\Delta}{E}\right)^{4/9}.$$

H = initial

Since the area in actual contact represents an insignificant part of the nominal area (10^{-2} to 10^{-5}), we will assume that the area of the gaseous layer is equal to S_H.

If the material of the granular system received a preliminary treatment, the height of the sphere $h_{Ш}$ will be determined by the class of cleanness of its surface. If the surface of the material was not first treated, the height of the sphere $h_{Ш}$ is determined experimentally. Tests made with gravel and lead-shot make it possible to expect a stable $h_{Ш}/d$ ratio, namely,

$$h_{Ш}/d = \gamma \cdot 10^{-3}; \ \gamma = 1 \div 3.$$

$Ш$ = sphere

Substituting the values of $h_{Ш}$ and S_H in the value of σ_2 we obtain an expression for the conductivity of the gaseous clearance

$$\sigma_2 = \lambda_r \frac{\pi d \cdot 10^2}{\Upsilon \beta^{2/3}} \left(\frac{\Delta}{E}\right)^{4/9}. \qquad (12)$$

r = gas

The heat transfer through the direct contact λ_k (through the hard body of the microroughness) is still determined only experimentally. An analysis of the experimental investigations shows that $\lambda_k = 1 \times 10^{-3}$ to 5×10^{-3} for nonmetallic particles and 0.3 to 0.5 for metals.

Into the large pore can be inscribed a sphere with a radius of 0.41 r [1]. Taking into account the gaseous aureoles, the radius $\left(r_\sigma\right)$ of the inscribed sphere will be equal to

$$r_\sigma = 0.41\,(r + \alpha) + \alpha.$$

Conditionally, the large pore will be regarded as a cylinder with a radius of r and a height of $2r_\sigma$. The molecular conductivity of such a cylinder is equal to

$$\sigma_3 = \lambda_r 2\pi r(1.41 A - 1).$$

With this expression the conductivity σ_3 is calculated for a porosity when the radius of the pore becomes equal to the radius of the particle, which corresponds to $\alpha/r = 0.41$ or to p = 75 percent.

For a porosity larger than 75 percent there appears a new channel of the transfer: a column of gas with a height of $rA\sqrt{2}$ and an area of $2r^2(2A^2 - \pi)$. Its molecular conductivity σ_5 is equal to

$$\sigma_5 = \lambda_r \frac{2r(2A^2 - \pi)}{\sqrt{2}A} . \quad (13)$$

Substituting in equation (4) the values of σ_i from equations (7), (12), (13), and λ_k it is possible to obtain an expression for the effective heat conductivity of the granular system. This expression, however, will still fail to reflect the heat transfer through the system because, as above, a number of essential phenomena have not been taken into account. We will proceed with the analysis of these phenomena.

a) The calculation of the conductivity of the gas σ_2 between the microrough portions did not take into account the dependence of σ_2 on the porosity, although it is obvious that an increase in porosity must reduce the value of σ_2. Let us use σ_2' for the true value of the sought conductivity, in which case

$$\sigma_2' = \sigma_2 f(p). \quad (14)$$

It is obvious that f(26 percent) = 1 and that f(100 percent) = 0.

Let us present f(p) in form of a difference between two functions $26/p - \varphi(p)$ and let us assume that $\varphi(p)$ varies linearly with p when passing through two points $\varphi(26) = 0$ and $\varphi(100) = 0.26$, in which case

$$f(p) = \frac{26}{p} - 0.0035p + 0.09.$$

b) Let us estimate the amount of heat carried through the gas by radiation. As shown by A. F. Chudnovskiy, the radiation component λ_p of an effective coefficient of heat conductivity in the i^{th} clearance can be calculated by using the expression [3]:

$$\lambda_{pi} = 2\epsilon_p^2 CT^3\delta_{mi} = g\delta_{mi}, \quad (15)$$

$$g = 9.2 \cdot 10^{-2} \left(\frac{T}{100}\right)^3 .$$

The additional conductivity σ_{pi} due to the radiation in the i^{th} gaseous element of the cell is equal to

$$\sigma_{pi} = \lambda_{pi} S_{mi} / \delta_{mi} .$$

In calculating the effective heat conductivity of the system by using a previous formula [4], it is necessary to add σ_{pi} to σ_i for i = 1, 2, 3, and 5.

c) The molecular heat transfer through a gaseous layer depends on many factors. As has been shown [4], the heat conductivity of a gas (λ_r) whose pressure varies widely can be calculated with the aid of the formula

$$\lambda_r = \lambda_0 \left[1 + \frac{4k}{k+1} (Pr)^{-1} \left(\frac{2-\alpha}{\alpha} \right) Kn \right]^{-1} . \tag{16}$$

$$r = gas$$

If A_1 is the length of the free path of a gas molecule under a pressure of H_1 = 133,322 H/m^2, then

$$\Lambda = \frac{\Lambda_1 H_1}{H} . \tag{17}$$

Taking into account the relationships (16) and (17), the expression for the heat conductivity λ_{ri} in the i^{th} layer can be written as:

$$\lambda_{ri} = \frac{\lambda_0}{1 + B/H\delta_{mi}} , \quad B = \frac{4k}{k+1} (Pr)^{-1} \left(\frac{2-\alpha}{\alpha} \right) \Lambda_1 H_1 .$$

It can be shown that in an elementary cell the expression for σ_{mi} and S_{mi} will be as follows:

$$\delta_{m1} = r \left(A - \frac{\pi}{4} \right), \quad S_{m1} = \pi r^2 ;$$

$$\delta_{m2} = h_{ш}, \quad S_{m2} = \frac{0.14 \pi d^2}{\beta^{2/3}} \left(\frac{\Delta}{E} \right)^{4/9} ;$$

$$S_{m3} = \pi r^2(1.41A - 1)^2, \; p \le 75\%;$$

$$\delta_{m3} = 2r(1.41A - 1), \quad S_{m3} = \pi r^2, \; p \ge 75\%;$$

$$\delta_{m5} = 2\sqrt{2}\, rA, \quad S_{m5} = 2r^2(2A^2 - \pi).$$

Ш = sphere

The final expression for an effective heat conductivity of a granular system assumes the following form:

at $26\% \le p \le 75\%$

$$\lambda_{e\phi} = \frac{\lambda_0}{A}\left(X + Y + 2.23\,\frac{1.41A - 1}{1 + B/H\delta_{m3}}\right) + \frac{4.45}{A}\,gr\,[1 + 0.5(1.41A - 1)^2] + \lambda_K;$$

at $p \ge 75\%$ (18)

$$\lambda_{e\phi} = \frac{\lambda_0}{A}\left[X + Y + 2.23\,\frac{1}{(1.41A - 1)\left(1 + B/H\delta_{m3}\right)} + \frac{A^2 - 1.58}{(1 + B/H \cdot 2.82rA)\,A}\right] + \frac{4.45}{A}\,gr\left(1 + \frac{A^2}{\pi}\right) + \lambda_K,$$

$e\phi$ = effective

where

$$X = \frac{4.45}{1 + B/H\delta_{m1}} \times \left(A \ln \frac{A}{A - 1} - 1\right);$$

$$Y = f(p)\,\frac{1}{1 + B/H\delta_{m2}} \times \frac{9.9 \cdot 10^2}{\Upsilon\beta^{2/3}}\left(\frac{\Delta}{E}\right)^{4/9}.$$

The formulae expressions (18) were used to calculate the coefficients of heat conductivity of various granular systems for a wide range of porosities and pressures of the filling gas. A satisfactory agreement was obtained between the calculated and experimentally checked values of the coefficient of heat conductivity of granular system (Figure 3).

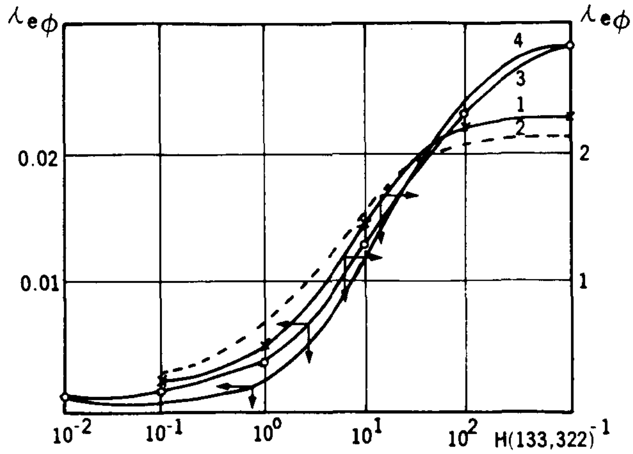

FIGURE 3. COMPARISON OF EXPERIMENTAL (1, 3) AND CALCULATED (2, 4) DATA

1) steel balls with a diameter of 1.26 mm in hydrogen at p = 35 percent [5]; 3) silica gel, d = 5-6 microns in air, p = 95 percent [5]; 2 and 4) steel balls and silica gel.

DESIGNATIONS

d — diameter of a particle; h — the height of elementary cell; 2α — the aureole thickness; p — the porosity of the system; 2y — the distance between particles; $\lambda_{e\phi}$ — the effective heat conductivity of an elementary cell; λ_r — the molecular heat conductivity of the gas in the clearance; λ_0 — the heat conductivity of the gas under normal pressure; R_i and σ_i — respectively, the heat resistance and conductivity of the i^{th} part of the elementary cell; σ_1 and σ_5 — the conductivity of the gaseous aureole and of the large pores; σ_{mi} — the average size of the clearance, in meters; S_{mi} — the average area of the i^{th} element; S_H — the nominal area of the contact (the area of the gas layer between the contacts); $h_{Ш}$ — the average height of the clearance (between the microrough portions); b — the convergence of the spheres; P_H — the contacting force; μ — Poisson's ratio of the material of the particles; E — Young's modulus of the material of the particles; ϵ_p — degree of blackness of the surface of the pores; C — a Stephan-Boltzmann constant; T — the average absolute temperature of the material; $k = c_p/c_v$ — the ratio of heat capacities of the gas at constant pressure and volume; α — coefficient of accommodation; A — the length of the free path of the molecules; H — the pressure of the filling gas.

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